SUPERSYMMETRIC ELECTROWEAK BARYOGENESIS AND CP VIOLATION

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I review the mechanism of electroweak baryogenesis within the framework of a string motivated supersymmetric extension of the Standard Model with large flavor-independent CP-violating phases. Possible implications for the Higgs sector are considered in correlation with the properties of the right-handed stop. I also comment on the compatibility of supersymmetric electroweak baryogenesis with various CP-violating observables.

One of the problems of the Standard Model is the long standing issue of the origin of CP violation. The only source of CP violation in the Standard Model comes from the phase δ in the CKM quark mixing matrix. Once this phase is determined from experiment it is, at least in principle, possible to make predictions for all CP-violating observables based on this one measurement. The Standard Model can then satisfy the necessary criteria – baryon number violation, C and CP violation and non-equilibrium conditions [1] – allowing for a non-zero baryon asymmetry to be generated in the universe at the electroweak transition. The baryon number violating interactions are introduced by non-perturbative weak sphaleron decays and the electroweak phase transition provides out-of-equilibrium conditions needed to preserve the generated asymmetry.

At high temperatures, the vaccum expectation value of the Higgs field is zero but as the universe cools down over time, a second minimum appears in the potential at $v \neq 0$. As the temperature decreases, the probability of making a transition from symmetric to broken phase grows and when the transition occurs at a certain point in space, a bubble of broken phase forms and expands. The baryon asymmetry is generated as the wall of the expanding bubble passes through points in space. Particles in the unbroken phase close to the wall interact with the changing Higgs field profile in the wall and the presence of CP-violating couplings produces source terms for participating particles. Different chiralities couple with different strength when CP is violated and a difference occurs in the reflection and transmission probabilities for the two different chiralities. Due to rapid gauge, Yukawa and strong sphaleron interactions, the CP-violating source terms are translated into a net left handed weak doublet quark density which is finally converted into a baryon asymmetry by weak sphaleron decays. The non-perturbative asymmetry then diffuses through the bubble wall into the broken phase where the weak sphaleron interactions are exponentially suppressed. Subsequent washout of the baryon asymmetry can therefore be kept under control provided the first order phase transition is strong enough [2].

Unfortunately, this scenario is not viable in the Standard Model since a small value of the vacuum expectation value at the critical temperature $v(T_c)/T_c < 1$ allows for the baryon asymmetry to be washed out unless the Higgs mass is below 60 GeV which is in direct contradiction with experimental limits. The situation can be improved in the Minimal Supersymmetric Standard Model (MSSM) as the light right handed top squark contribution to the temperature dependent effective potential can push the value of $v(T_c)/T_c$ up to acceptable values ≥ 1 even for light Higgs masses allowed by experimental searches.

The CP-violating interactions in the MSSM arise in the complex phases of the soft supersymmetry breaking terms in the Lagrangian and in the phase of μ. These phases have to be small, typically $\lesssim 10^{-2}$, if they are considered individually with sparticle masses $\mathcal{O}(\text{TeV})$, otherwise they induce contributions to the electric dipole moments (EDMs) of the neutron and electron exceeding experimental limits. Recently it has been shown, however, that these stringent limits can be avoided in the Type I string models with non-universal gaugino masses as a result of a particular embedding of the Standard Model gauge group into two D-brane sectors [3,4]. The relations among soft breaking parameters ensure cancellations of individual contributions to the EDMs and viable large phase solutions can be obtained over a wide range of parameter space as illustrated [4] in Fig.1. Moreover, the two gaugino mass phases $\varphi_1 = \varphi_3$ (in our parametrization $\varphi_2 = 0$), the μ parameter phase φ_μ and the overall trilinear parmeter phase φ_A are *flavor-independent* at the string scale making it possible to separate the physics of CP violation from flavor physics.

The dominant sources of CP-violation that are relevant to the electroweak baryogenesis scenario come from the interactions of the Higgs fields with charginos and neutralinos. These interactions couple the Higgsino and gaugino components of charginos and neutralinos and involve potentially large CP-violating phases originating from the mixing. The combined Higgsino source term is then expressed as

$$\mathcal{S}_{\tilde{H}} = 3\gamma_{\tilde{W}} \sin(\varphi_\mu) + \gamma_{\tilde{B}} \sin(\varphi_1 + \varphi_\mu) \tag{1}$$

where

$$\gamma_{\tilde{W}} = |\mu||M_2| g_2^2 v^2(X) \dot{\beta}(X) \mathcal{I}_{\tilde{W}}, \tag{2}$$

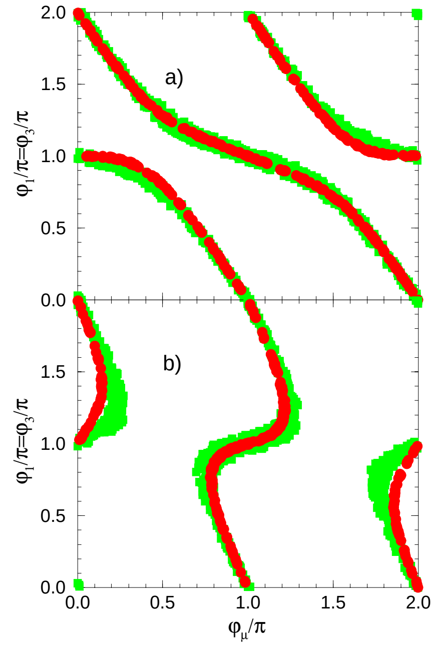

Figure 1: Electron (red (black) circles) and neutron (green (grey) blocks) EDM allowed regions for the Type I orientifold models with $m_{3/2} = 150\,\mathrm{GeV}$, $\theta = 0.4$, $\Theta_1 = 0.9$ and $\tan\beta = 2$. In frame a) the values of B and μ are assumed to be independent and their magnitudes are set to $|B| = 100\,\mathrm{GeV}$ and $|\mu| = 600\,\mathrm{GeV}$. Frame b) shows the results for the case when electroweak symmetry is assumed to be broken radiatively.

$$\gamma_{\tilde{B}} = |\mu||M_1| g_1^2 v^2(X)\dot{\beta}(X)\mathcal{I}_{\tilde{B}}. \tag{3}$$

The phase space integrals $\mathcal{I}_{\tilde{W}}$ and $\mathcal{I}_{\tilde{B}}$ can be evaluated in terms of the soft breaking parameters entering the chargino and neutralino mass matrices [5]. It is important to emphasize that the phases factorize from the rest of the source term and enter independently of the particular details going into the calculation of the Higgsino thermal production rate. For a light superpartner spectrum the produced baryon density to entropy density ratio n_B/s can be as big as 10^{-7} compared to the observed value of 4×10^{-11}. Recently identified new terms in the Higgsino thermal production rate [6] can increase the produced asymmetry even more so the upper limit of 10^{-7} should be viewed as a conservative estimate.

Since the baryon asymmetry is overproduced at the time of phase transi-

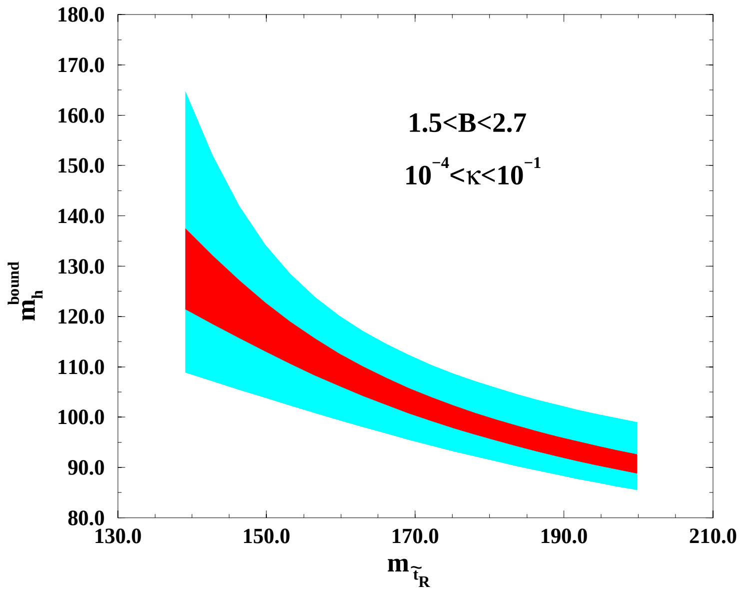

Figure 2: Dependence of the upper Higgs mass bound on the light right handed stop mass. The width of the bands results from uncertainties in the weak sphaleron parameters B and κ which are varied in the full range. The central band corresponds to B=1.87 while κ is varied in the full range.

tion some of it has to be washed out by sphaleron decays in the broken phase. Defining $\zeta_c \simeq 36\frac{v(T_c)}{T_c}$ the washout equation [7] is for a given value of n_B/s

$$\zeta_c - 6\log\zeta_c - \log\kappa - 9\log 10 - \log 4.1 + \log(\log\frac{n_B/s(T_c)}{4\times 10^{-11}}) \gtrsim 0. \qquad (4)$$

The lower limit for $v(T_c)/T_c$ obtained by solving this equation is related to the soft SUSY breaking parameters determining the position of the temperature dependent potential minimum. Therefore, it can be translated into an upper limit on the lightest Higgs mass [8] which itself is a function of the right-handed stop mass as shown in Fig. 2. A significant uncertainty is introduced by the estimated range of the weak sphaleron decay parameters in the broken phase B and κ.

The results indicate that by including large CP-violating phases in the calculation of the baryon asymmetry the light Higgs masses can be pushed towards larger values which can easily accomodate experimental limits even for relatively heavy ($\sim 200\,\mathrm{GeV}$) right-handed stops. In the case of the Type I string model the EDM cancellation mechanism requires small values of $\tan\beta$, which constraint the largest possible light Higgs mass, and Fig. 2 can be used to estimate the implied range of the stop mass. Regions with large light Higgs mass limits and light stops might be relevant in non-minimal supersymmetric extensions of the Standard Model.

The idea of the supersymmetric origin of CP violation can be extended even further. Assuming that the CKM matrix is (approximately) real and only flavor-independent CP-violating phases occur in the MSSM it is possible to construct a flavor structure for the squark mass matrices at low energies which is required for consistency with the observed values of ϵ, ϵ'/ϵ and the preliminary experimental value of $\sin 2\beta$. At the same time, this framework would lead to theoretical predictions such as $\sin 2\beta = -\sin 2\alpha$ which should be experimentally testable [9].

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